Solar activity and ionospheric response as seen from combined SolACES and SDO-EVE solar EUV spectra.

Ch. Jacobi[1], B. Nikutowski[1,2], J. Hein[1], C. Unglaub[1], Ch. Erhardt[2], R. Brunner[2], G. Schmidtke[2]

[1]*Institut for Meteorology, Stephanstr. 3 04103 Leipzig, E-Mail: jacobi@uni-leipzig.de*
[2]*Fraunhofer-Institut für Physikalische Messtechnik (IPM), Heidenhofstraße 8, 79110 Freiburg*

Summary: Ionospheric response to solar EUV variability during late 2012 through mid 2013 is shown by the EUV-TEC proxy based on combined SolACES and SDO/EVE solar spectra. The results are compared with global TEC analyses. We found that EUV-TEC describes TEC variability better than the conventional F107 index, especially during periods of strong solar flare activity.

Zusammenfassung: Der Einfluss solarer EUV-Variabilität auf die Ionosphäre im Zeitraum Ende 2012 bis Mitte 2013 wurde mit Hilfe des EUV-TEC-Proxys dargestellt. Eingabedaten waren kombinierte SolACES und SDO/EVE-Spektren. Verglichen wurden die Ionisationsraten mit globalen TEC-Analysen. Es zeigt sich, das EUV-TEC die ionosphärische Variabilität besser repräsentiert als konventionelle Indizes wie F10.7, besonders während Zeiten starker solarer Aktivität.

1 Introduction

The solar extreme ultraviolet (EUV) radiation varies on different time scales, with the 11-year Schwabe sunspot cycle and the 27-day Carrington rotation cause the primary variability. Consequences are strong changes of ion content of the upper atmosphere. The ion content may be described by the Total Electron Content (TEC), which is the integrated electron density over height and often given in term is TEC Units (TECU, 1 TECU = 10^{16} electrons/m^2). The majority of the electrons are found in the ionospheric F layer where, according to simple theory, electron density is proportional to the ionization rate. Therefore, TEC variability is a coarse estimate for ionization as well, so that indices describing ionization may be compared against ionospheric TEC.

Solar variability is often described by simple indices like F10.7, which is defined as the solar radio emission at a wavelength of 10.7 cm, although the primary factor that controls TEC variations and the variability of thermospheric density and temperature is the solar EUV radiation (Emmert et al., 2010, Maruyama, 2010). Furthermore, a nonlinear relationship between F10.7 and EUV fluxes is found (e.g., Liu et al., 2011). Therefore, especially under solar minimum conditions, conventional indices may not well describe the EUV radiation and there is a need for updated EUV indices to describe the ionospheric variability.

In this work we present the EUV-TEC proxy (Unglaub et al., 2011, 2012), which is intended to explain solar induced ionospheric variability. EUV-TEC is calculated here from combined SolACES and SDO/EVE spectra. The proxy will be compared against F10.7 and the global mean TEC.

2 Measurements and data analysis

EUV measurements from SolACES and SDO-EVE

The Solar Dynamics Observatory (SDO) was launched on 11 February 2010 (Pesnell et al., 2012), and data are available from 1 May 2010. The Extreme Ultraviolet Variability Experiment (EVE) onboard SDO measures the solar EUV irradiance from 0.1 to 105 nm with a spectral resolution of 0.1 nm, a temporal cadence of ten seconds, and an accuracy of 20% (Woods et al., 2012). The EVE Level 3 products are averages of the solar irradiance over a day and over each one-hour period.

SolACES (Schmidtke et al., 2006, 2014) is part of the ESA SOLAR ISS mission. Since the successful launch aboard the shuttle mission STS-122 on February 7th, 2008 the instrument is recording the short-wavelength solar EUV irradiance from 16 to 150 nm during the extended solar activity minimum and the first half of solar cycle 24 with rising solar activity and increasingly changing spectral composition. The SOLAR mission is extended from a period of 18 months to more than 8 years until end of 2016. SolACES is operating three grazing incidence planar grating spectrometers and two three-current ionization chambers. Re-filling the ionization chambers with different gases repeatedly and using overlapping band-pass filters the absolute EUV fluxes are derived in these spectral intervals. This way the problem of continuing efficiency changes in space-born instrumentation is overcome during the mission.

To calculate combined spectra, SDO-EVE version 4 daily spectra are used together with SolACES spectra. Between 16 and 58 nm the spectral fluxes are averaged, when SolACES spectra are available. For the other observations, a correction factor for SDO-EVE at 22.5 nm was determined using the spectra between 16 and 29 nm. This factor has been used for the other wavelengths by linearly extrapolating it so that is reached unity at 125.5 nm. We use data from day 296/2912 through day 181/2013.

EUV-TEC proxy

The EUV-TEC proxy represents the vertical and globally integrated primary ionization rates calculated from spectral EUV fluxes between 16 and 105 nm. EUV-TEC is calculated from satellite-borne EUV measurements assuming a model atmosphere that consists of four major atmospheric constituents. Regional number densities of the background atmosphere are taken from the NRLMSISE-00 climatology. For the calculation the Lambert-Beer law is used to describe the decrease of the radiation and absorption and finally ionization along their way through the atmosphere. The EUV-TEC proxy thus describes the ionospheric response to solar EUV radiation and its variability. Details of the EUV-TEC calculation are given in Unglaub et al. (2011, 2012).

Global TEC analyses

To estimate, to which degree EUV-TEC or F10.7 mirrors the ionospheric variability, the proxies will be compared against a global daily mean TEC. To determine TEC, the ionospheric influence on GPS radio wave propagation paths can be used, because it depends on the radio wave frequency. Thus, using the two GPS frequencies the ionospheric electron density integrated along the radio wave propagation path can be determined. Using a network of ground-based GPS receivers, measured TEC, after applying a mapping function to convert the slant TEC into vertical TEC values, the latter can be defined as the height integrated electron density between the ground and the satellite orbit (e.g. Aggarwal, 2011). We use data from gridded vertical TEC maps recorded with the IGS tracking network (Hernandez-Pajares et al., 2009), and calculate the average global TEC from these.

3 Results and discussion

The ionization rates calculated from SolACES/SDO-EVE spectra were normalized by subtracting the mean and dividing by the standard deviation taken from days 310/2012 – 162/2013 (Nov. 4, 2012. – Jun. 11, 2013, approx. Carrington rotations #2130 - 2137). The same normalization was done for the F10.7 solar radio fluxes and the global TEC values. The mean values and standard deviations are $1.79 \cdot 10^{19} \pm 1.34 \cdot 10^{18}$ ions/m^2 for the ionization rates, 118.2 ± 17.6 sfu for F10.7, and 26.67 ± 3.51 TECU for TEC.

The indices are shown in Figure 1. In the lower part of the figure, the number of daily solar flares is shown also. The latter have been provided by NOAA, Space Weather Prediction Center (SWPC), through http:// www.swpc.noaa.gov/ftpdir/indices, and are taken here as a proxy to describe the disturbance of the solar atmosphere at short time scales. Both EUV-TEC and F10.7 qualitatively show the same seasonal cycle and the solar rotation effect. One can see from the figure, that deviations between EUV-TEC and F10.7 are primarily seen when the sun is very disturbed, so, for example, in early January 2013.

Scatter plots of EUV-TEC and F10.7, respectively, vs. global mean TEC are shown in Figure 2. One can see that the correlation for EUV-TEC is slightly stronger, and the slope is closer to unity. However, since the major source of variability is the 27-day solar rotation which is qualitatively well reproduced in both datasets, the differences are not very large, if analyzed that way.

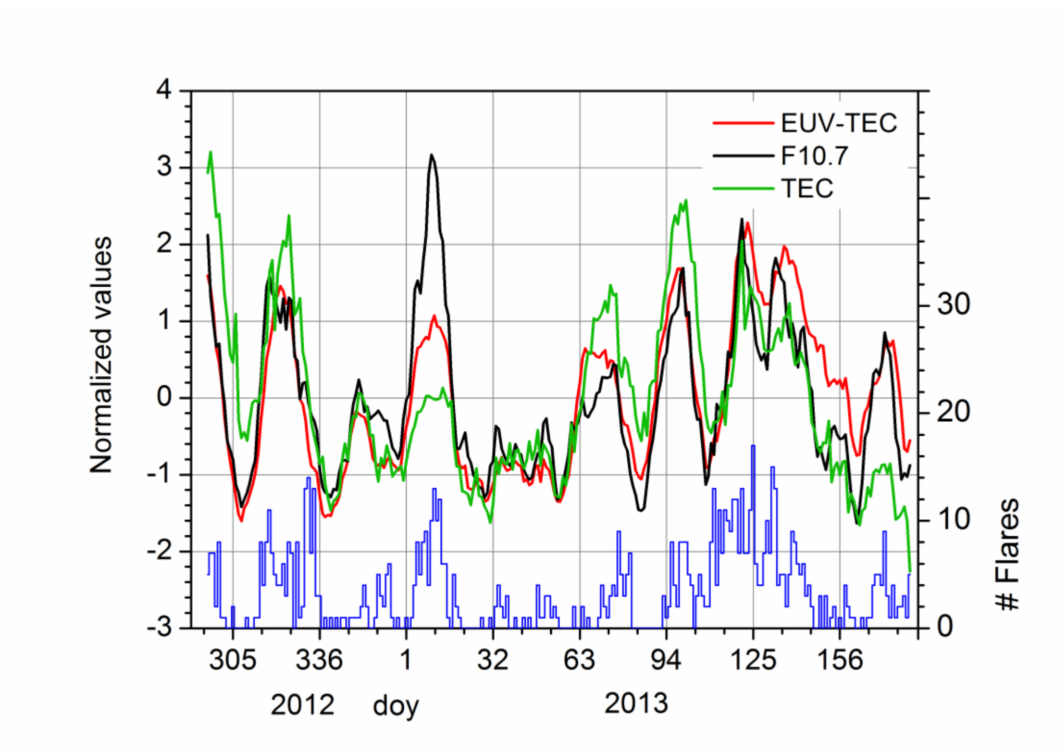

Figure 1: Time series of EUV-TEC proxy, normalized F10.7 solar radio flux, and normalized global TEC values. The number of flares is given in the lower part of the panel.

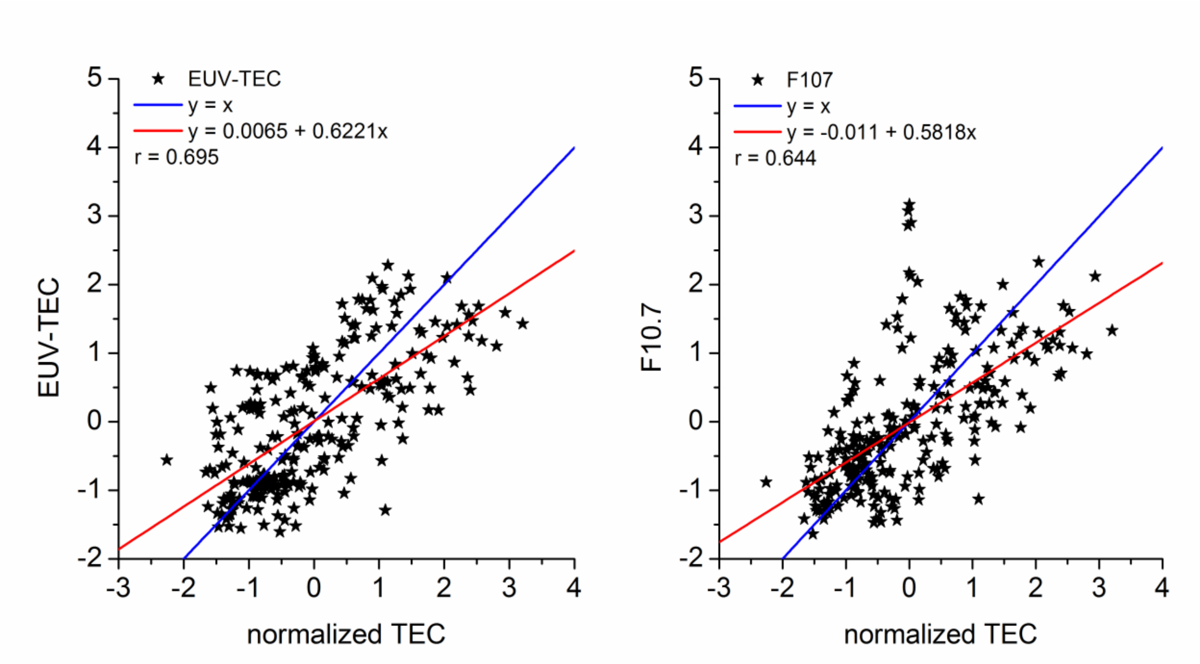

Figure 2: EUV-TEC proxy vs. normalized global TEC values (left) and normalized F10.7 solar radio flux vs. normalized global TEC values (right). The y=x lines are shown in blue, and linear least-squares fits are added as red lines. The correlation coefficients of the fits are given in the figures.

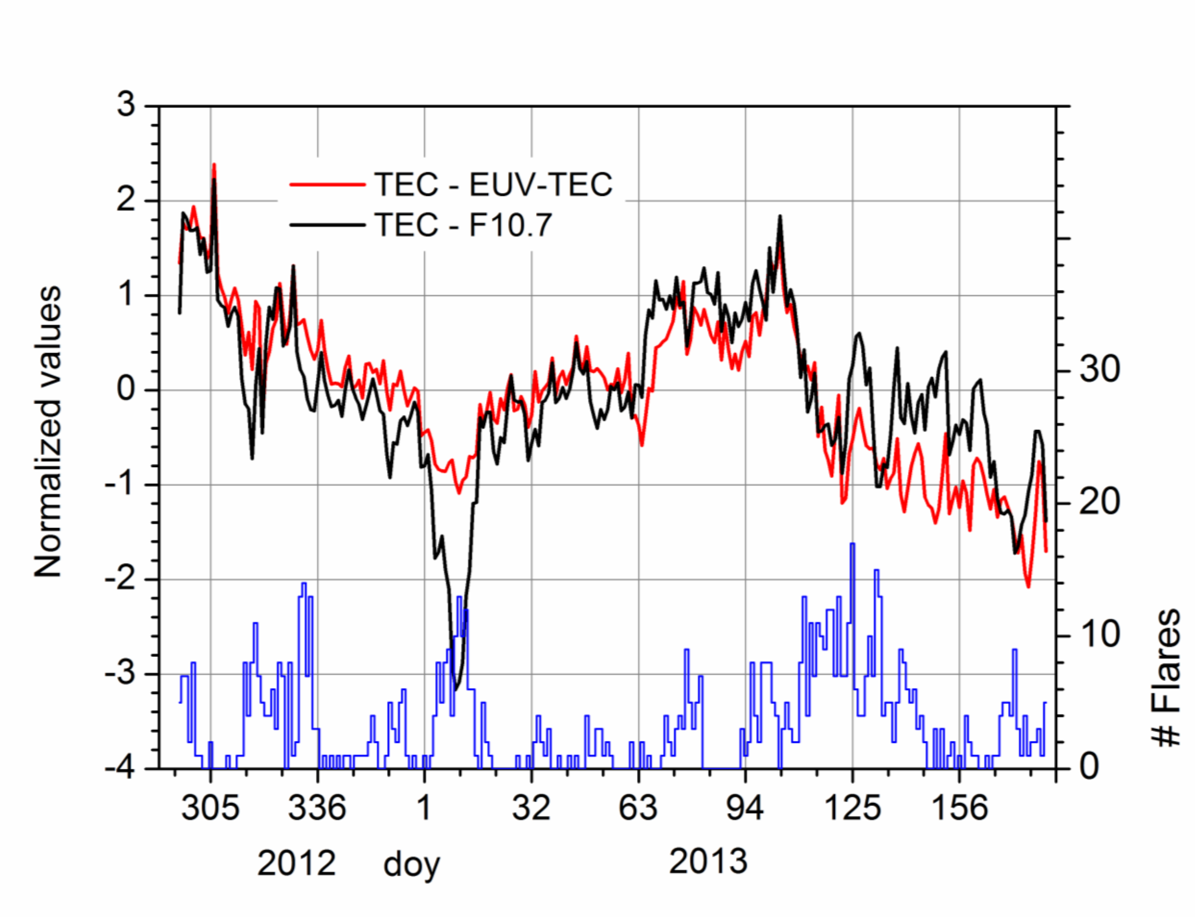

Figure 3: Time series of the differences between normalized global TEC values and the EUV-TEC proxy (dashed) and normalized F10.7 solar radio flux (solid), respectively. The number of flares is given in the lower part of the panel.

In Figure 3 we show differences between the normalized TEC and both solar EUV indices, which should be small if the indices were to be used as a proxy for ionization. Both time series show a seasonal variability with positive values during equinoxes and negative ones during solstice. This is due to the semiannual component of the seasonal TEC cycle, which is of dynamical origin and not represented in solar EUV (see also Unglaub et al., 2011). One can also see that during the second half of the time interval considered there is a tendency that TEC – F10.7 values are slightly larger than TEC – EUV-TEC values. This is due to the very large F10.7 values (or very strongly negative TEC – F10.7 values, resp.) during the first half of January 2013 that lead to a positive bias in the normalization procedure. Therefore, the absolute unfiltered values shown in Fig. 3 cannot be considered as a direct measure for the quality of the proxy. However, from visual inspection of Fig. 3 one may see that during times of enhanced solar flare activity there is a tendency that F10.7 is increased and therefore the difference TEC – F10.7 is decreased. This is apparently not that clearly seen for EUV-TEC.

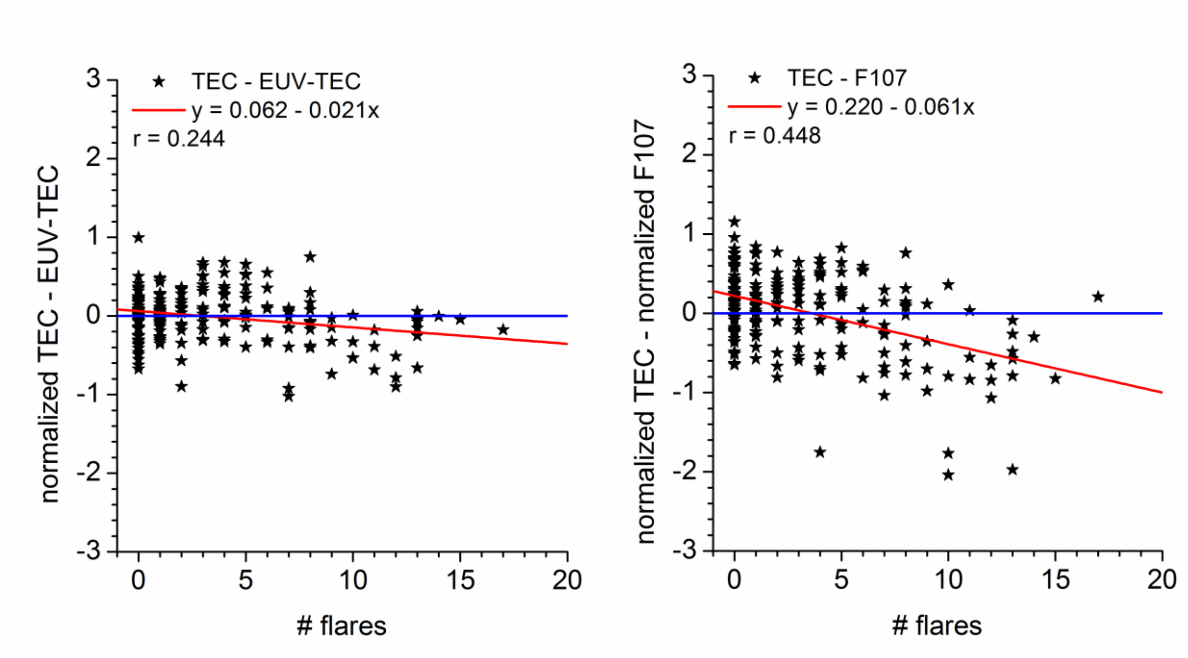

Figure 4: High-pass filtered differences between normalized TEC and EUV-TEC proxy (left) and normalized F10.7 solar radio flux (right) vs. the number of flares per day. The zero lines are shown in blue, and linear least-squares fits are added as red lines. The correlation coefficients of the fits are given in the figures.

In Figure 4 the differences between normalized TEC and EUV_TEC (left) and normalized F10.7 (right) are plotted against the number of solar flares. The differences now have been high-pass filtered using an FFT filter with a cutoff frequency of 0.01852 d^{-1} (period 54 days) to eliminate the seasonal cycle and a potential bias as discussed above. As expected from Fig. 3, the differences between TEC and EUV-TEC are largely independent of the number of flares, while differences between TEC and F10.7 decrease for days of strongly disturbed sun. Thus we may conclude that there is an influence of solar flares on F10.7, which is not evident in EUV spectra and does not affect global ionization. Therefore, using EUV-TEC is superior to using F10.7 at time scales of solar flare activity.

5 Conclusions

We have calculated the EUV-TEC proxy (Unglaub et al., 2011, 2012) from combined EUV spectra observed by SolACES and SDO-EVE. The proxy has been compared with global TEC results. We found that during times of strong solar flare activity EUV-TEC describes global ionization better than the F10.7 index does. At longer time scales the solar rotation effect in TEC is similarly well described by both EUV-TEC and F10.7. The seasonal cycle of TEC has a semiannual component not determined by EUV radiation, so that there is a semiannual cycle in the difference between global TEC and both F10.7 and EUV-TEC.

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